A COMPARISON OF TRACKING WITH VISUAL AND KINESTHETIC-TACTUAL DISPLAYS

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ABSTRACT

Recent research on manual tracking with a kinesthetic-tactual (KT) display suggests that under appropriate conditions it may be an effective means of providing visual workload relief. In order to better understand how KT tracking differs from visual tracking, both a critical tracking task and stationary single-axis tracking tasks were conducted with and without velocity quickening. On the critical tracking task, the visual displays were superior; however, the KT quickened display was approximately equal to the visual unquickened display. Mean squared error scores in the stationary tracking tasks for the visual and KT displays were approximately equal in the quickened conditions, and the describing functions were very similar. In the unquickened conditions, the visual display was superior. Subjects using the unquickened KT display exhibited a low frequency lead-lag that may be related to sensory adaptation.

INTRODUCTION

The question is often asked, Are the aircraft of the future to use <u>only</u> automated control? Are we at the point of using only pushbutton inputs into intelligent flight control circuitry--without manual control at all--the ultimate fly by wire? Not today at least--even the space shuttle has a traditional control yoke (although the throttles are non-existent in this brick-like glider). Thus manual tracking control still has its place in today's current and envisioned aircraft.

How do we provide information in the cockpit? Presently via two traditional senses--the eyes and ears--overburdened as they may be with the barrage of information in this high speed, complex and heavily used mode of travel. The other modalities of information input are, of course, the senses of smell, taste, and touch. While the first two (smell and taste) are currently impractical for communication or control, some little research has been devoted to touch as an informational channel. The bulk of tactile research has centered on language for the blind (e.g. Braille); however, some research during the last decade has addressed the use of touch (e.g., electrocutaneous, vibratory) as a means for compensatory tracking in aircraft (e.g., attitude, glideslope). One of the more successful techniques has been a kinesthetic-tactual (KT) display (Figure-1) invented by Professor Robert Fenton of The Ohio State University

Department of Electrical Engineering (Fenton, 1966; Fenton and Montano, 1968). Simulator and inflight testing (Gilson and Fenton, 1974; Gilson, Dunn, and Sun, 1977) suggested considerable promise for this KT display as a substitute for visual displays of flight control information, particularly during periods of visual distraction. By presenting information to multiple modalities, it may be possible to increase a pilot's overall workload capability. For example, a recent laboratory investigation (Burke, Gilson, and Jagacinski, 1980) of a two-handed tracking task has shown an advantage for a combination of KT and visual displays over a two-dimensional visual display.

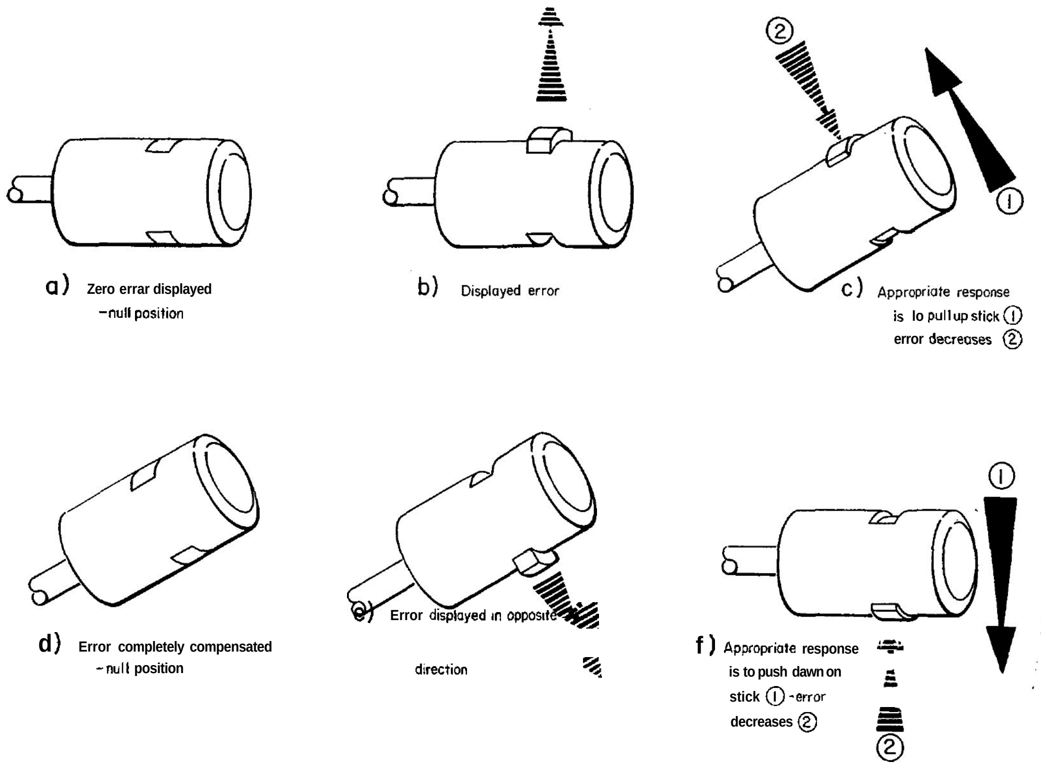

Figure 1. Display-response relationship for the KT display. (Copyright 1979, Human Factors, Vol. 21, p. 80)

The current study is an attempt to analyze the characteristics of the KT display and the operator in order to measure describing functions that may generalize across displays. Subjects were first practiced on a critical tracking task (Jex, McDonnell, and Phatak, 1966) using ST and visual displays with and without velocity quickening. Subjects were then transferred to a stationary tracking task involving either a rate controller (single integrator plant) or a first-order unstable system, and linear describing functions were derived from their performance. The direct and practical benefit of this engineering/psychological approach is to point out favorable control tasks for implementing the tactual display, point out similarities and differences in the operator's use of visual versus tactual displays, and perhaps give some insights as to display characteristic optimization for future designs.

METHOD

Subjects

Thirty-two right-handed undergraduates were chosen on the basis of a pretest described below and then were assigned to one of eight experimental conditions. Subjects either received credit for an undergraduate laboratory requirement for up to four experimental sessions or were paid $2.50 per session.

Apparatus

Visual and KT displays were used with and without velocity quickening. The visual display consisted of a 1 cm long horizontal line that moved vertically on a Tektronix Type 602 CRT display. The center of the display was indicated by a 1 mm x 18 mm strip of yellow tape. Full scale was ±4 cm, which corresponded to ±3.76° of visual angle. The KT display was built into the cylindrical handle of the control stick, and consisted of a servo-controlled solid rectangular section (1.25 cm x 2.2 cm x 3.8 cm long) sliding in and out of the handle (Figure 1). Excursions from the flush surface of the control handle indicated the direction and magnitude of system error. Full scale was ±1 cm. For the quickened displays the ratio of position to velocity was 1:1.

The control stick was an isotonic lever arm that was 52 cm long from the pivot point to the center of the KT display. The control stick moved in a vertical plane at the left side of the seated subject and resembled a helicopter collective control. The range of angular travel was ±10°, with 20° above horizontal representing the neutral control position. The control stick was counterbalanced and had a nominal level of friction so that no force was necessary to maintain any angular position. Approximately 250 gm of force was necessary to move the stick from an initially stationary position.

Pretest

Eight groups of eight to ten subjects each were pretested on a critical tracking task (Jex, et al., 1966) using an unquickened visual display and a small isotonic control stick that required wrist movements performed with the right hand. The four subjects in each group with the best performance over the last 15 out of 45 trials were chosen to continue in the experiment.

Critical Tracking

The eight groups of four subjects performed 45 critical tracking trials per day for seven days. Subjects sat in a 2.1 x 1.5 m room with low ambient light for the visual displays and in total darkness for the KT displays. White noise heard through a headset masked auditory cues from the KT display servo-drive. On each trial subjects used their left hands to manipulate a control stick which resembled a helicopter collective. The control stick gain was .56° of visual angle for the visual display and .15 cm for the KT display per 1° of control stick movement. The subjects' task was to maintain control of a first order unstable system as its time constant-was progressively shortened over the course of a trial. No input signal was provided because the subjects' manual unsteadiness was sufficient to perturb the unstable system. The error signal, i.e. any deviation from zero output, was presented on one of four displays: two groups used an unquickened KT display; two groups used a quickened KT display; two groups used an unquickened visual display; and two groups used a quickened visual display. For the quickened conditions, the display gain was halved in order to keep the display range comparable to the unquickened conditions. For the KT display conditions a red warning light visible to both the subjects and experimenter was turned on whenever subjects held the KT display tightly enough to impede its movement.

The inverse of the time constant of the first order system, λ, was linearly increased over the course of a trial at .05 r/s^2 until the subjects allowed the error signal to reach full scale. At that instant the trial was terminated, and the value of the inverse time constant, referred to as the critical root, λ_c (Jex, et al., 1966), was displayed to the subjects and recorded as the performance measure. For the quickened displays it was the true system error, rather than the displayed quickened error, which was used to determine the end of a trial. The value of λ at the start of a trial was chosen to be approximately 1.5 r/s less than the value of λ_c on the immediately preceding trials, so that each trial lasted approximately 30 s. The trials were administered in three blocks of 15, with a two-minute break between blocks.

Stationary Tracking

Following the seven days of critical tracking, subjects were transferred to three days of stationary tracking. Subjects used compensatory displays of the same types used in their critical tracking tasks, with the exception that the red warning light was omitted from the KT display conditions, and the display gain for the quickened conditions was not halved. The system dynamics were either a single integrator, $1.5/s$, or a first-order unstable system, $3.0/(s-1)$. The static gain of the control stick was $1.41°$ of visual angle or .375 cm of KT display displacement per $1°$ of control stick movement for the $1.5/s$ system. The static gain was twice these values for the $3.0/(s-1)$ system. The input signal consisted of a sum of nine sinewaves with the amplitudes of the three lowest frequency sinewaves (.35, .73, 1.08 r/s) five times greater than the amplitudes of the other sinewaves. Subjects performed eight three-minute trials per day for three days. After each trial subjects were told their integrated squared error and received a one-minute break before the next trial. A $5 bonus was given to the subject in each display group having the lowest error score on the last day of the experiment.

RESULTS

Critical Tracking

The median value of λ_c was calculated for each block of trials for each subject on the seventh day of critical tracking. The mean of these medians for each group of subjects is shown in Figure 2. An analysis of variance performed on the mean λ_c scores revealed statistically significant main effects of sensory modality and quickening ($p < .01$) with no significant interactions. There was also no effect of the system dynamics to which the subjects were assigned for the subsequent stationary tracking. These results closely resemble those obtained by Jagacinski, Miller, and Gilson (1979) with the exception that performance with the KT displays is noticeably better given this extensive amount of practice. Based on these results, one would expect the visual displays to be better than or equal to the KT displays for the stationary tracking.

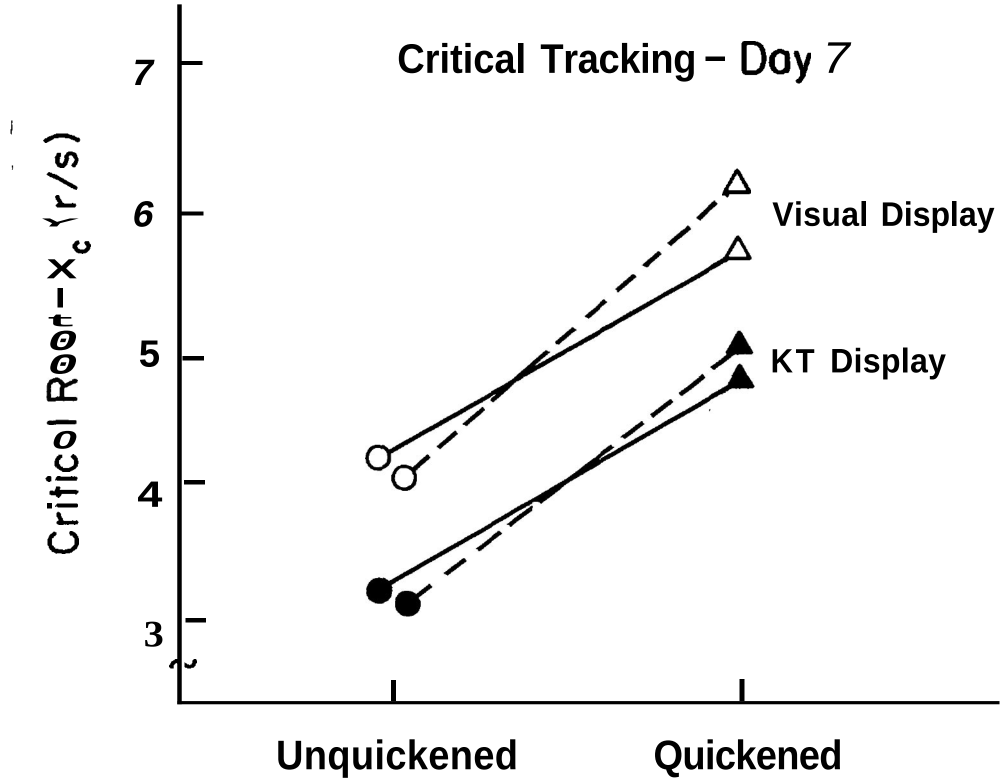

Figure 2. Critical tracking scores for eight groups of four subjects. Groups connected by dashed and solid lines respectively transferred to stationary tracking with system dynamics 1.5/s and 3.0/(s-1).

Stationary Tracking

The mean of each subject's mean squared error scores normalized by mean squared input for the third day of stationary tracking are shown in Figure 3. One subject who used an unquickened KT display was unable to perform the stationary tracking task with 3.0/(s-1) dynamics, and this subject is omitted from Figure 3 and all subsequent analyses.

Quickened Displays. For the quickened display conditions, individual differences among subjects were relatively small, and differences between the visual and KT displays were small. An analysis of variance revealed no statistically significant main effects or interactions ($p > .10$). A describing function was derived for each subject by calculating Φ_{ic}/Φ_{ie} at each of the nine input frequencies (McRuer, Graham, Krendel, and Reisener, 1965). Φ_{ie} is the cross spectral density of input and displayed error, and Φ_{ic} is the cross spectral density of input and control stick position. The mean amplitude ratio and mean phase shift were calculated from four trials of Day 3 of stationary tracking. These means are displayed as circles in Figure 4 for the four subjects having the lowest mean squared error in their respective display conditions.

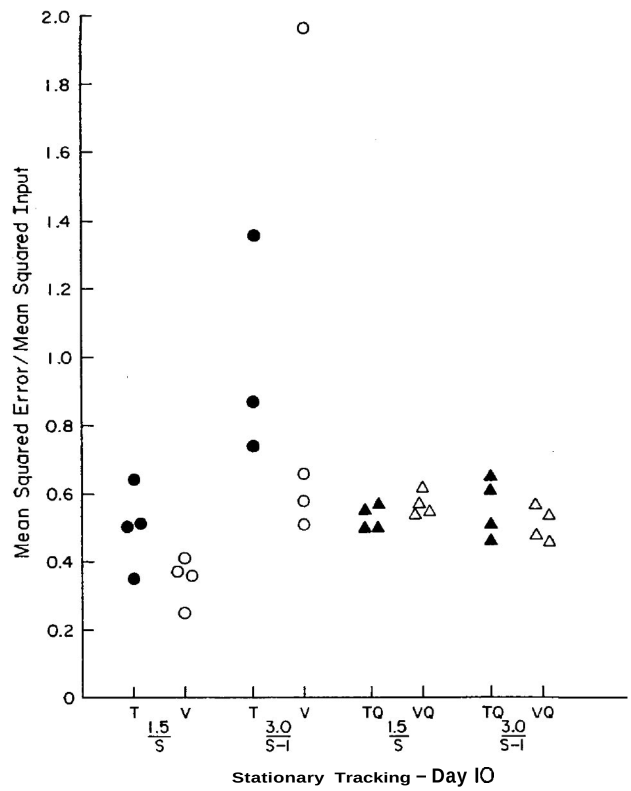

Figure 3. Mean squared error normalized by mean squared input for thirty-one individual subjects. The symbols represent the same display conditions as in Figure 2.

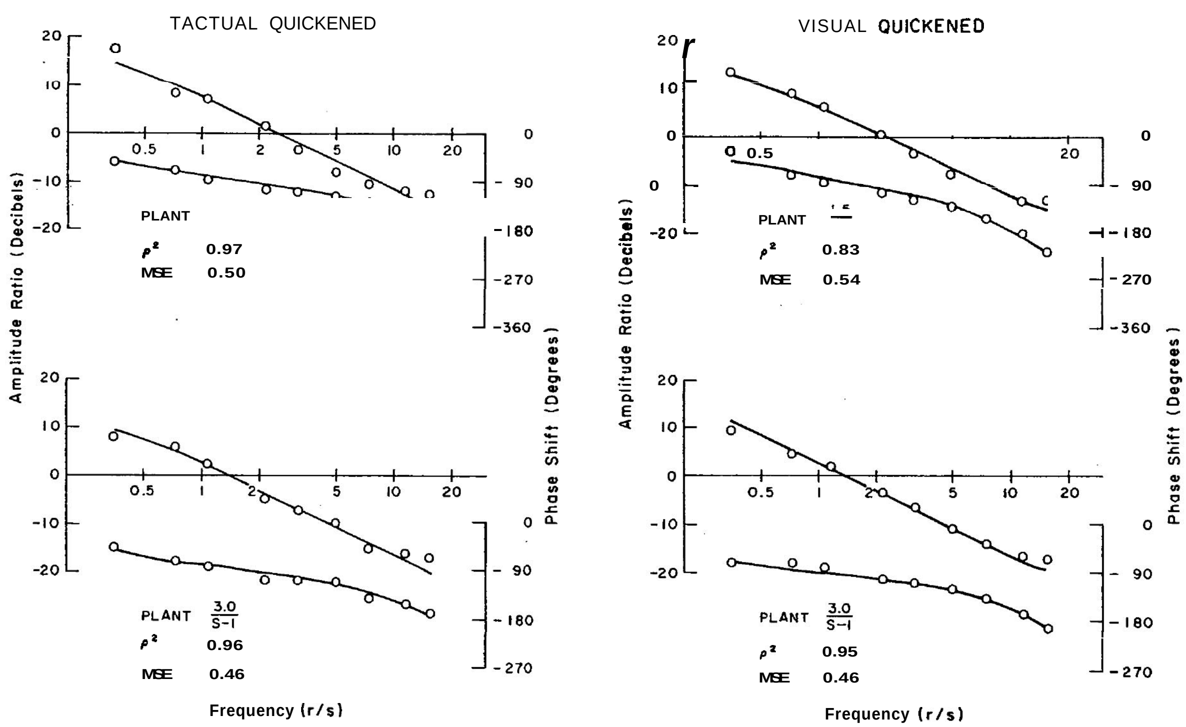

Figure 4. Linear transfer functions for the subjects with the lowest mean squared error in each of four quickened display conditions. The circles indicate the data points, and the solid lines represent analytic approximations consisting of a low frequency lag, a high frequency lead, a gain, and a time delay.

These describing functions are well approximated by a low frequency lag, a high frequency lead, a gain, and a time delay. Values of these parameters were chosen to maximize the proportion of variance accounted for among the amplitude ratios plus the proportion of variance accounted for among the phase shifts. For each subject in Figure 4, the linear transfer function resulting from this parameter search is represented as a solid line. For four of the sixteen subjects the high frequency lead was effectively absent. These four subjects were distributed across three experimental conditions, and all of these subjects had the highest or next to highest mean squared error in their respective groups. Across the quickened conditions, the visual and KT describing functions were very similar.

The proportion of variance of each subject's control that was linearly correlated with the input was estimated as

$$\rho^2 = \sum_{n=1}^{9} \tfrac{1}{2} I^2(\omega_n)[\Phi_{ic}(\omega_n)/\Phi_{ii}(\omega_n)]^2 / \overline{C^2}$$

(McRuer, et al., 1965). $I(\omega_n)$ is the amplitude of the input sinewave at frequency ω_n, $\Phi_{ic}(\omega_n)$ is the cross spectral density of input and control at this input frequency, $\Phi_{ii}(\omega_n)$ is the auto power spectral density of the input at this frequency, and $\overline{C^2}$ is the mean squared control. The mean value of ρ^2 averaged across subjects ranged from .86 to .94 for the four quickened display conditions.

The describing function for the KT display was calculated from the command signal to the display and the display response as indicated by a follower-potentiometer coupled to the slide. This describing function was well approximated by a first-order lag with a break frequency of 18.5 r/s and a time delay of .01 s. The display lag is not included in the describing functions for the KT subjects in Figure 4.

Unquickened Displays. For the unquickened display conditions, there were large individual differences in mean squared error with the 3.0/(s-1) dynamics, which precluded using an analysis of variance. Therefore, a *t*-test was used for the 1.5/s system, and a non-parametric test was used for the highly variable data with the 3.0/(s-1) system. A *t*-test comparing the visual and KT displays with the 1.5/s dynamics indicated a tendency for the visual display to yield lower mean squared error ($t = 2.2$, $p < .05$, one-tailed). For the 3.0/ (s-1) dynamics, if one ignores the single outlier in the visual condition, then all three of the remaining visual subjects performed better than the three KT subjects. A Mann-Whitney *U*-test indicates that this result is also statistically significant ($U = 0$, $p = .05$, one tailed).

The median amount of control used by the groups of subjects with the unquickened displays ranged from 3.32 to 6.76 root mean squared degrees of stick movement. This amount of control is considerably greater than for the groups of subjects with the quickened displays, whose median root mean squared control ranged from 1.49 to 2.50 degrees. For the unquickened displays, the proportion of variance in the control movements linearly correlated with the input frequencies was considerably less than for the quickened displays. For the 1.5/s dynamics, the mean value of ρ^2 was .69 for the unquickened visual display and .42 for the unquickened KT display. Inspection of power spectra of the control movements of subjects using the KT display revealed from one to three strong peaks occurring at non-input frequencies in a region from approximately 3 to 7 r/s. Corresponding peaks were sometimes present, but considerably smaller in the control spectra of subjects using the visual display. This control activity may represent relay-like control superimposed on more nearly linear tracking behavior. For the 3.0/(s-1) dynamics, the mean value of ρ^2 was .68 for the unquickened visual display and .69 for the unquickened KT display. There was some evidence of peaks occurring in the control spectra at non-input frequencies for this KT group, but these peaks were much smaller than with the 1.5/s dynamics.

Describing functions for the subjects with the lowest mean squared error in their respective unquickened display conditions are shown as circles in Figure 5. The data are well approximated by linear transfer functions consisting of a low frequency lag and lead, a high frequency second-order lag, a gain, and a time delay. Subjects using the KT display generally exhibited less phase lag at the three lowest frequencies. This difference from the visual display conditions can be modeled as an additional lead-lag for the KT group. The describing function for the electromechanical KT display itself was the same as in the quickened conditions. The KT display lag is not included in the describing functions of the KT subjects in Figure 5.

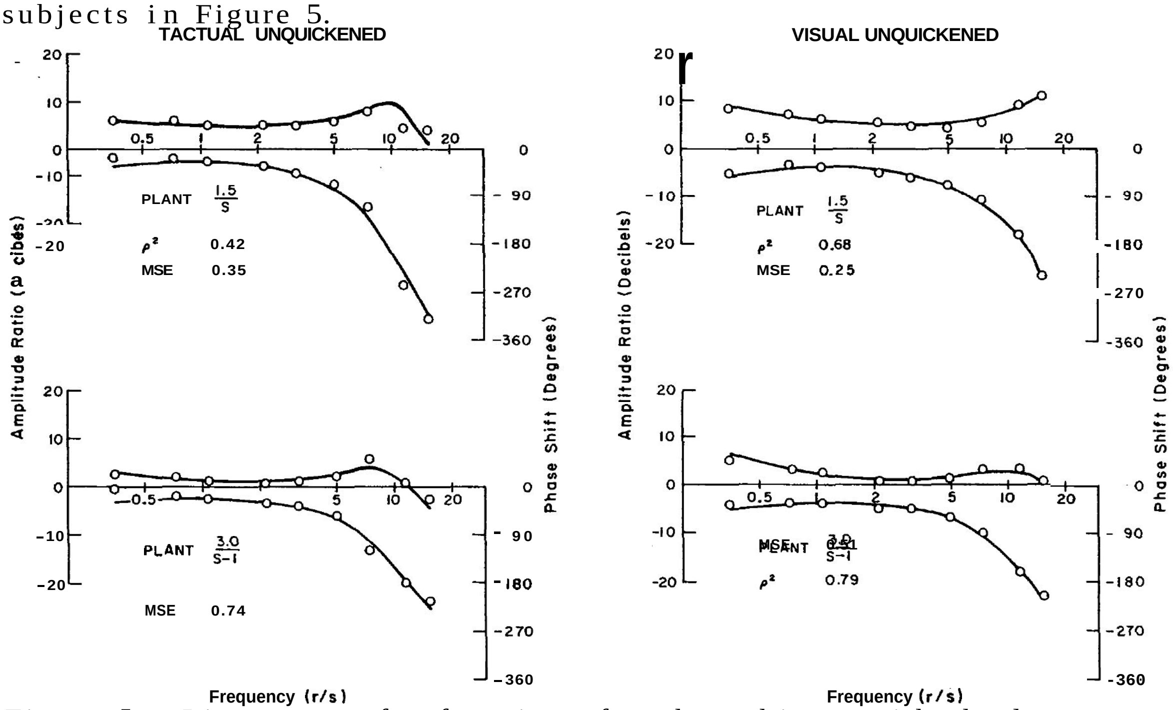

Figure 5. Linear transfer functions for the subjects with the lowest mean squared error in each of four unquickened display conditions. The circles indicate the data points, and the solid lines represent analytic approximations consisting of a low frequency lag and lead, a high frequency second-order lag, a gain, and a time delay.

DISCUSSION

The quickened visual displays yielded better performance than the quickened KT displays in the critical task, but the two displays yielded approximately equal performance in the stationary tracking tasks. The results of Burke et al. (1980) suggest that the difference in critical task performance with the quickened displays is primarily due to the electro-mechanical lag of the KT servo-drive. It may be that with increasingly unstable systems or with input signals of higher bandwidth the stationary tracking results would also reflect the ordering found in the critical task. However, tracking simulations based on the describing functions of subjects with the KT lag removed from the system suggest that the electro-mechanical lag contributed little to the obtained error scores in the quickened KT conditions. These stationary tracking tasks involved relatively little control movement, the display moved relatively rapidly due to the quickening, and subjects' behavior was strongly linearly correlated with the input signal. The describing functions were well approximated by a low frequency lag, a high frequency lead, and a time delay, and there was surprisingly little difference in this pattern between modalities.

For the unquickened displays, subjects performed better with the visual display in the critical task and in the stationary tracking tasks as well. Tracking simulations suggest that the electro-mechanical KT display lag contributed little to the error scores for the 1.5/s system, but may account for approximately half the difference in error scores between KT and visual unquickened displays with the 3.0/(s-1) system. This stationary tracking involved a good deal of control movement, the displays moved more slowly than the quickened displays, and subjects' behavior was much less linearly correlated with the input. The describing functions were well approximated by a low frequency lag and lead, a high frequency second-order lag, and a time delay. Differences between the visual and KT describing functions at low frequencies were well approximated by an additional lead-lag for the KT describing functions. This pattern may be indicative of a kind of rapid sensory adaptation (Milsum, 1966) in the kinesthetic-tactual sensory system that is not present in the visual system. In other words, the KT sensory system may be relatively more sensitive to velocity than position stimuli, and this factor probably contributed to the differences in error scores with the unquickened displays.

A display technique that might enhance velocity cues and/or reduce non-linearities in the KT sensory system is to add a high frequency, low amplitude vibration to the KT display. The frequency would have to be high enough that this signal would not be confused with error correlated with the input signal. Whether this technique does in fact improve performance with the unquickened KT displays remains to be tested.

In summary, the present experiments have shown that with quickened displays and a low input bandwidth tracking performance is approximately equivalent with visual and KT displays for a single integrator and first-order unstable systems. With unquickened displays, the visual modality is superior. This superiority may be due to the KT modality being relatively more sensitive to velocity rather than position cues as well as to the electro-mechanical lag in the KT display.

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